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Quarter Scale RLV Multi-Lobe LH2 Tank Test Program

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Abstract

Thirty cryogenic pressure cycles have been completed on the Lockheed Martin Michoud Space Systems quarter scale RLV composite multi-lobe liquid hydrogen propellant tank assembly, completing the initial phases of testing and demonstrating technologies key to the success of large scale composite cryogenic tankage for X33, RLV, and other future launch vehicles.

Introduction

Single-stage-to-orbit (SSTO) concepts have all identified two key enabling technologies: high performance engine development and advanced composite cryogenic propellant tankage. Lockheed Martin Michoud Space Systems (LMMSS) has been addressing the composite tankage development and the potential system impacts to reusable launch vehicles.

During the Reusable Launch Vehicle (RLV), Phase 1 Technology Program, a task was initiated by LMMSS to demonstrate the unique features of composite tankage baselined for the RLV lifting body vehicle through design, fabrication and test of a quarter scale RLV liquid hydrogen (LH2) tank. The composite tank design, analysis, tooling, fabrication, assembly, inspection, instrumentation and test initiation was successfully performed in less than a year, resulting in rapid prototyping of the largest, most complex composite cryogenic tank tested to date.

Testing of the composite quarter scale tank at the NASA Stennis Space Center (SSC), consisted of cryogenic pressure cycling with liquid hydrogen to achieve RLV/X33 Technology Demonstrator (X33) flight pressures and strains. The test setup allowed stringent monitoring of tank performance with respect to structural integrity and LH2 containment through conventional and state-of-the-art vehicle health monitoring (VHM) sensor systems. Test objectives included demonstration of large-scale composite tank technologies as a function of cryogenic pressure cycles. To date, 30 cryogenic pressure cycles have been successfully completed toward demonstration of mission life requirements on large-scale composite tankage.

Background

The RLV lifting body vehicle shape (reference Figure1) mandates non-cylindrical tank structures. Multi-lobed tank configurations were chosen during RLV Phase1 to meet vehicle packaging efficiency requirements and maintain efficient circular cross sections for pressure. Stringent vehicle mass fraction requirements drive the tanks to be structurally efficient, lightweight and durable for multiple missions to support RLV objectives of low cost reusability. Newly developed toughened composite materials are key to achieving these mass fractions. The composite tanks must contain LH2 under unique structural loading conditions (cryogenic pressure, vehicle fuselage bending and vehicle landing loads) unlike any other pressure vessels to date. In essence the aircraft fuselage structure is coupled with propellant tank requirements to form RLV cryogenic tank structure.

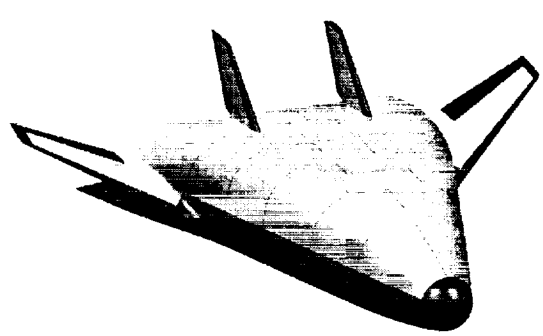

Figure 1. Lockheed Martin Reusable Launch Vehicle (RLV)

A multidivisional, multidiscipline tank team, established by LMMSS, was tasked to develop a large-scale composite multi-lobed demonstration tank test article and test program to address RLV cryogenic tank structure. The quarter scale RLV composite multi-lobed LH2 tank test program was established.

Composite cryogenic tank technologies, developed under Lockheed Martin (LM) Internal Research and Development and the National Aerospace Plane program (NASP), were used as the jumping off point for configuration development and development testing. See Figure 2.

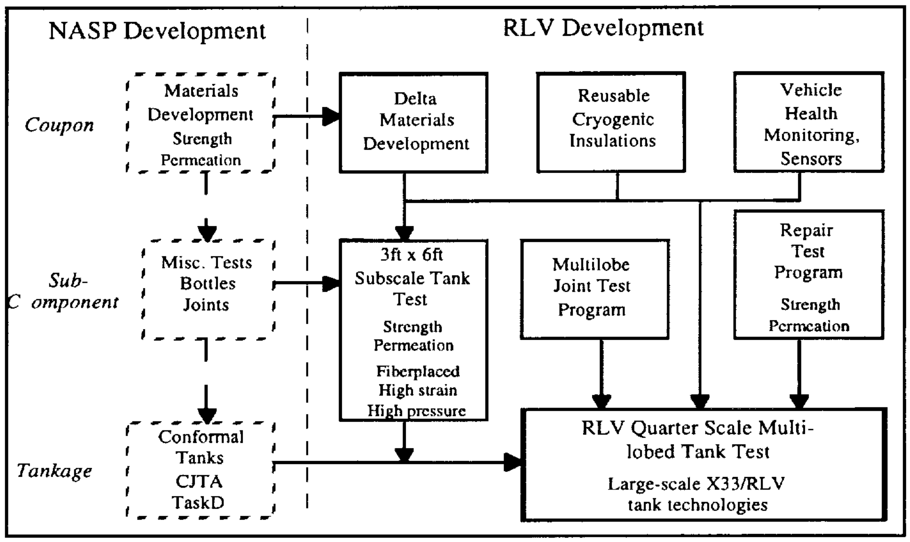

Figure 2. Quarter Scale RLV Composite Cryogenic Tank Development Test Program

Quarter Scale RLV Composite Multi-lobed LH2 Tank Test Article Assembly

The composite multi-lobed tank test article (approx. 1/4 scale of RLV, 1/2 scale of X33) was designed to enable evaluation of tank technologies on a representative scale. The composite tank test article (Reference Figure 3), measuring 10 ft wide and 17 ft long, consists of two cylindrical lobes joined at a 10-degree angle.

The tank includes many X33/RLV candidate structural characteristics. Fabrication processes include fiber placement, cure forming, cobonds, secondary bonds, and large scale machined surfaces. Design configurations include lobed tankage, complex geometry, mechanically sealed lobe joint, cobonded dome to barrel joints, cocured metallic bosses, secondarily bonded stiffeners and ring frames, manhole covers, and miscellaneous fittings.

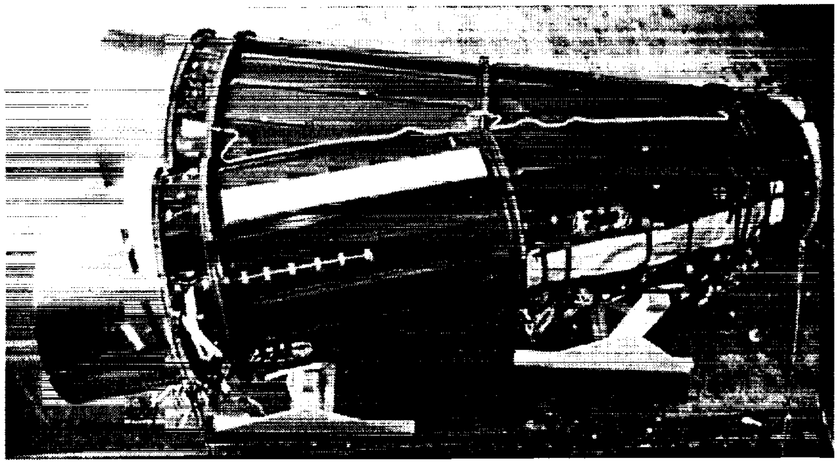

Figure 3. Quarter Scale RLV Composite Multi-lobed Tank

The quarter scale RLV composite multi-lobed LH2 tank test article assembly consists of the tank test article integrated with both conventional and X33/RLV candidate tank systems. See Table 1. RLV mission life requirements mandate that the integrated tank and systems perform under extensive cryogenic cycling conditions.

Table 1. Tank Systems

System	Conventional	X33/RLV Candidate
Cryogenic Insulation	Space Shuttle External Tank Insulations	Reusable Insulation Systems
Instrumentation, VHM	Strain Gages Thermocouples	Strain Gages-Proprietary Installation Distributed Strain Sensors Distributed Temp. Sensors
Level Sensors	Point Sensors	Capacitance Sensors
Leak Repairs	N/A	MSS Proprietary Liner Filled, Unfilled Coatings Prepreg, Wet Lay-up

Quarter Scale Tank Testing

The primary objective of the quarter scale RLV composite multi-lobed tank test was to demonstrate and evaluate the performance of large scale composite tank structure and associated tank systems as a function of cryogenic pressure cycles. The secondary objective was to establish a tank systems database in order to support X33/RLV vehicle operations.

Testing was conducted at the NASA SSC Test Facility (see Figure 4). Testing consisted of 30 cryogenic cycles, achieved by filling the tank test article with LH2 and pressurizing with GH2. The tank was pressurized to X33/RLV tank operating pressures and then pressures were increased to obtain X33/RLV representative strain levels.

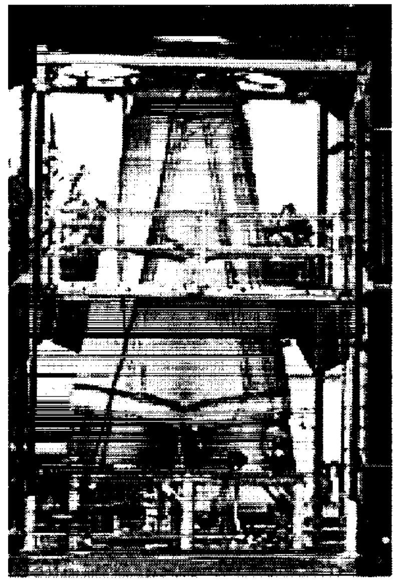

Figure 4. Composite Multi-lobed Tank in SSC Test Facility

Ambient pressurization with GHe and GH2 was conducted for proof pressure, for local permeability and leak assessments, and to obtain permeability and leak data for comparison to existing coupon, subcomponent, and acceptance test databases.

Performance of the composite multi-lobed tank test article and tank systems was stringently monitored during testing for evaluation against RLV derived requirements and environments. See Table 2.

Table 2. Tank Performance Evaluation

X33/RLV Derived Tankage Requirements			**Quarter Scale RLV Tank Test Program**	
Requirement	*X33*	*RLV*	*Quarter Scale Tank*	*Evaluation/Monitoring System*
Mission Life Cycles	50	600	30 (to date)	Instrumentation, Data Acquisition System, Inspection
Thermal Environment	-423°F to +350°F	same	-423°F to ambient	Thermocouples, Distributed Temperature Sensors, Infrared
Structural Environment	5 to 36 psi 4000µ	same 6000µ	5 to 100 psi 4000 -6000µ	Valve pressure transducers Strain Gages, Distributed Strain Sensors, Acoustic Emission
LH2 Containment	4% H2 concentration	same	Individually bagged test zone requirements	Facility Mass Spec. (H2, He: 30ppm-4%) Microelectronic Sensors (H2: 3.5-100%) Portable Mass Spec. (He: 10^{-7} to 10^{-5}scc/s) Bubble Leak Check (He: $\geq 10^{-3}$scc/s)

Tank Test Article Performance

Overall the composite tank and systems out performed any composite cryogenic tank test hardware to date. The stringent techniques employed to monitor tank performance revealed tank system anomalies and issues that impact vehicle operational performance.

Structural Performance

On a subscale pressurized structure either the structural cross sections or the loading must be scaled to obtain equivalent internal loads. The quarter scale test tank utilized RLV full scale structural cross sections and components (i.e. skin thickness) to adequately represent materials and processes and increased pressure to obtain RLV scale loads. Conventional and VHM systems were installed in representative typical and peak strain areas as predicted by a NASTRAN finite element model (FEM) of the tank test article.

In general, repeated cryogenic cycles appeared to have little affect on laminate strain. Tank strains were linear with pressure, were consistent with analytical predictions and from test to test. Tank thermal gradients monitored through thermocouples, DTS and infrared systems closely followed analytical predictions.

This supports the assumption that composite tank structures in general can be scaled up to meet RLV loads as a function of the material selected being capable of sustaining multiple cryogenic load cycles at high strain to reach tank weight goals. High strain levels at cryogenic temperatures were demonstrated previously on the LMMSS subscale 3-foot tank test and on coupons. The quarter scale tank test verified this performance on a large-scale representative tank structure.

Continued development is required in the area of structural joints for large-scale tanks. The most highly loaded joint on the quarter scale tank, the longitudinal lobe to lobe joint, was designed as a mechanically fastened sealed joint. It was sized for full scale RLV loads and is structurally scaleable. The joint performed well structurally with the exception of two local delaminations and the cause for the delaminations must be further investigated. Large scale, adhesively bonded joints were demonstrated on the quarter scale tank including the dome to barrel circumferential joints and hat/frame to barrel bondlines. These joints, however did not see the load levels associated with RLV scale joints (4000-12000 lb/in at -423°F). Note also, that though they performed well structurally during the test, there was local leakage at relatively low load levels, 1500-2000 lb/in, in areas of complex geometry (areas difficult for tooling and processing and of complex loading), which did not affect structural performance. Bonded joints, are limited with respect to load carrying ability based on allowable strain levels of existing adhesives at cryogenic temperatures. Further development of bonded joints is currently in progress on the X33/RLV program.

LH2 Containment Performance

Unlike metallic materials, composite materials are measurably permeable with respect to helium and hydrogen. This has implications for tank design, tank test methodologies, and vehicle system requirements. Historically, H2 leakage is taken as the sum of the leak rates through joints including line flange joints, manhole joints, etc. Tank surface and adhesive joint permeability must also be taken into account and managed for large-scale composite cryogenic tankage through future launch vehicle systems architecture.

Previous coupon and subscale testing has shown tank surface permeability to be very low, approximately 10^{-5} to 10^{-7} scc/sec/in^2, which meets current criteria for 4% cavity H2 concentrations. Adhesive joints with thin bondlines have been demonstrated to have permeability rates similar to the tank surface. The challenge with adhesive joints on a large scale is to manage the manufacturing tolerances so that the tolerance stack up does not lead to thick bondlines, which have demonstrated unacceptable leak rates.

Containment was monitored and quantified during the quarter scale tank test by bagging the tank into large zones and measuring zone leak rates. Local leak tests using a portable mass spectrometer and bubble leak tests were performed to isolate areas of the tank with relatively high permeation rates and to monitor the performance of subsequent leak repair systems.

The tank acreage and the majority of the tank cobonds sustained a low permeability rate throughout the 30 cryogenic test cycles consistent with coupon and subscale tank test data, thereby demonstrating scale-up of composite tank integrity with respect to LH2 containment. In addition, the mechanically bolted lobe to lobe joint sealed interface contained LH2 as predicted by subscale test, demonstrating the continuous compression seal joint concept on a large-scale multi-lobed tank. These nominal permeation rates are acceptable with respect to current X33/RLV cavity concentration allotments.

However, repetitive cryogenic cycling initiated local LH2 leakage in areas of complex geometry, structural discontinuity, bonded joints, and laminate anomalies (i.e. resin dry areas and wrinkles), all of which are common characteristics of large-scale composite tankage not usually present in coupon or subcomponent hardware. This anomaly leakage results in H2 concentrations greater than 4% in the vehicle cavity, as presently designed. All leaks detected were mapped and labeled on the tank. It should be noted that the leak detection methods determine the exit location of a leak not the source. These areas were monitored continuously as part of the large bagged zones and locally after each five cryogenic cycles.

The leak anomalies demonstrated different physical and leak characteristics as a function of pressure and cycles depending on their location and cause. The leaks in general increased in rate as a function of cryogenic cycles and increasing pressures. With the exception of those leaks caused by detectable process anomalies (i.e. wrinkles, dry areas), leak anomalies were not detectable using conventional NDE. Most leaks were not detected by ambient proof and were not detected in the first cryogenic cycles.

In summary, nominal composite tank and tank joint LH2 permeability rates are acceptable to the vehicle, but composite tanks are leak sensitive to damage and manufacturing anomalies, and areas of complex geometry, structural discontinuity, and joints are potentially prone to anomaly leakage. This anomaly leakage must be addressed further with respect to tank design, containment repairs, tank test and inspection methodologies, and vehicle systems management of H2 leakage.

LH2 Containment Repairs

Numerous candidate repair methods were installed on the tank test article to evaluate their performance with respect to survivability and LH2 containment as a function of cryogenic pressure cycles. The repair materials and processes included the secondarily bonded LMMSS proprietary liner, filled and unfilled cryogenic coatings, prepreg, and wet lay-up. The variables considered when defining alternative leak repair materials and processes included effects of cryogenic cycling, strain levels and tank geometry constraints.

These methods were tested and monitored through 20 cryogenic cycles. The LMMSS proprietary liner successfully performed throughout the 20 test cycles. Other repair methods demonstrated limited mission life capabilities. Enhanced repair techniques continue to be investigated in parallel on subcomponent tests and in the quarter scale tank.

X33/RLV Candidate Tank Systems

Candidate X33/RLV tank systems, including Reusable Cryogenic Insulation (RCI), Propellant Level Sensors, and Vehicle Health Monitoring (VHM) systems, were evaluated and demonstrated on the quarter scale test article with respect to their capability to survive and perform under cryogenic cycling conditions as part of the integrated tank assembly. In each system, testing on the quarter scale tank led to refinements beneficial to future use of the system on X33/RLV composite tankage.

Candidate RCI systems were bonded to the tank test article to demonstrate large acreage and local close-out configurations. The primary candidate performed well over the 30 cryogenic test cycles. The closeout candidate performed poorly during initial testing, and compatibility issues were indicated between the insulation and the baseline adhesive. The closeout was reformulated and new adhesive configurations were developed. The primary insulation, as acreage coverage, and the reformulated close-out, were bonded to the tank surface over X33/RLV candidate VHM sensors to represent a flight configuration. Both performed well over 20 cryogenic cycles.

The Capacitance Liquid Level Sensor System was successfully demonstrated in the quarter scale tank test. Capacitance probes were installed on a sensor mast together with conventional point sensors. The results of the test validated the function of the capacitance system and provided data required to refine system accuracy analysis for X33/RLV.

VHM sensors including Distributed Strain Sensors (DSS), Distributed Temperature Sensors (DTS), and Acoustic Emission (AE) Sensors were bonded to the tank wall, and DTS were bonded to the RCI, to represent the flight configurations. Data from DSS and DTS was evaluated with respect to conventional instrumentation results. DTS testing led to development of an adhesive system that improved the life and performance of the fibers. DSS testing led to enhancements to the DSS hardware device and development of a bondline method that decreases signal loss along the fiber. AE testing resulted in development of an alternate adhesive system. In addition, a method was developed and demonstrated that allows for check out of non-accessible AE sensors (i.e. sensors covered by RCI or within a tight compartment space, which are likely scenarios for X33/RLV).

Summary

Advanced composite cryogenic propellant tankage has been identified as a key enabling technology for SSTO RLV. The LMMSS quarter scale RLV composite multi-lobe LH2 tank was successfully tested. The tank test provided critical supporting data feeding development of second generation X33 LH2 composite tankage and the on-going technology database required for successful development of an RLV vehicle. The tank and systems database generated to date has been deemed "breakthrough technology" key to understanding composite structural tanks and the impacts to RLV vehicle systems and operations.

Principal Author Biography

Celia Blum is a senior staff engineer at LMMSS with 14 years experience in design, analysis, and test of composite aerospace structures. Particular areas of experience include development of composite structures under elevated and cryogenic conditions for programs including Space Shuttle External Tank, X33, RLV, and research and development. She holds a 1995 patent for Cryogenic Tank Liners and was responsible for analysis and test of the Quarter Scale RLV Composite Multi-lobed LH2 Tank.

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